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MOORING SYSTEM INTEGRITY IN EXPOSED LOCATIONS AND NARROW CHANNELS

John Flory
Tension Technology International LLC
4 Tower Lane
Morristown, NJ 07960
973-267-0871
Flory@TensionTech.com

Steve Banfield
Tension Technology International Ltd
69 Parkway, Eastbourne,
East Sussex, BN20 9DZ, UK
44-1323-504167
Banfield@TensionTech.com

ABSTRACT

Larger vessels are now being moored at terminals which are exposed to high waves and in channels which are subjected to passing-ship-induced forces. These situations increase mooring line wear and loads and sometimes cause mooring failures.

This paper will discuss some of the associated problems and some of the solutions.

Use of high-performance fiber ropes instead of wire ropes can decrease mooring loads. These mooring line ropes can be handled by fewer people. The risk of injuries is greatly reduced.

When properly cared for, these fiber ropes last longer than wires in service. But fiber ropes are vulnerable to abrasion damage, especially in vessel fairleads. Special nylon fairlead liners are now available to eliminate this wear problem.

Fiber rope tails are used on mooring lines to increase stretch and reduce peak loads. Greater vessel motions at exposed location moorings have caused cyclic loading fatigue in nylon tails. Industry recommendations have now been clarified to allow the use of longer nylon tails and of polyester tails. More durable nylon tails are now available.

Larger vessels entering into and mooring along confined channels increase the risks of passing ship problems. Passing-ship induced forces increase with vessel size and with the greater speed at which larger vessels must pass in order to maintain steerage.

Computer mooring analyses should be conducted to ensure that mooring arrangements are adequate. These analyses should account for effects of waves at exposed locations and should include appropriate passing-ship forces.

This paper will be of interest to designers and operators of large vessels and of marine terminals intended for such vessels.

INTRODUCTION

This paper discusses recent studies and findings which relate to the integrity of pier-side moorings [1] for tankers, gas carriers and other large vessels in exposed locations and passing-ship channels.

Mooring analysis normally only considers the wind and current forces and moments induced on the vessel. Constant wave drift force is sometimes considered, but time-varying wave-induced vessel motions are usually not considered.[2] Also, time-varying passing-ship forces and the resulting motions are usually not considered.

Until recently, large vessels usually moored only alongside piers in protected harbors or behind breakwaters. But during the last decade, terminals for large vessel have been placed in exposed locations where they are affected by waves and swell.

Similarly, larger vessels entering ports can increase passing-ship problems. The larger vessel must pass closer to moored vessels to remain in the channel and must pass at a higher speed to maintain steerage. Also, the larger vessel's size increases the forces and moments induced on the moored vessel.

Large vessels traditionally used steel wire ropes for mooring. But at moorings in exposed and passing-ship locations, the wire ropes can be highly tensioned and fatigued by vessel motions. Wire ropes are heavy and can have broken wires, and thus they are difficult and hazardous for deck crew to handle.

High-performance synthetic-fiber ropes are a light-weight, safer alternative to wire ropes.[3] There are potential problems with their use, but these problems can be understood, resolved, and eliminated.

This paper first discusses potential mooring system problems at terminals in exposed-locations and in passing-ship channels. It explains why fiber rope mooring lines may be desirable. It discusses solutions to the problems encountered with fiber rope, especially wear in fairleads. It explains the need for dynamic computer mooring analysis.

EXPOSED LOCATION MOORING PROBLEMS

Vessels have traditionally moored alongside piers in protected harbors or behind breakwaters or have only moored at open-water piers in mild wave environments. But larger vessels, particularly tankers and gas carriers, are now being moored at piers and sea islands in locations exposed to relatively high waves. This is done because sheltered harbors are not available and break waters are costly, and also because of concerns with bringing these vessels into congested ports.

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1 Use of the word pier in this paper generally also refers to quay wall, sea island, and mooring alongside another vessel.

2 Use of the term wave in this paper generally also includes swell.

3 In this paper, high-performance fiber rope refers to ropes made of aramid (e.g. *Kevlar*, *Twaron*, *Technora*), high-modulus polyethylene - HMPE (e.g. *Spectra*, *Dyneema*), and liquid crystal polymer (e.g *Vectran*). Italicized words are trade names of respective fiber materials.

Figure 1 Slack Mooring Lines

Figure 2 Taut Mooring Lines

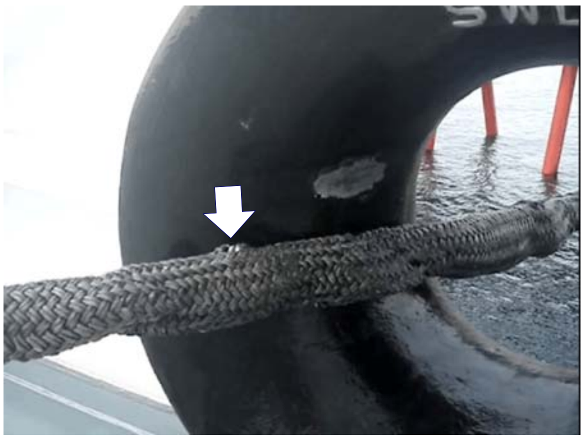

Figure 3 Slack Line in Fairlead

Figure 4 Taut Line in Fairlead

These exposed-location moorings have not been without problems. Waves induce greater vessel motions and cause mooring lines to wear and fail.

Figure 1 shows slack breast lines on a vessel moored in a swell environment. Figure 2, taken a few moments later, shows these breast lines under high tension due to vessel motion.

Figure 3 shows a slack fiber-rope mooring line passing through a fairlead on the vessel. Figure 4, taken a few moments later, shows this mooring line under high tension. Wear caused by rubbing of the line through the fairlead can be seen just above the slack line in Fig. 3.

Comparing Figs. 3 and 4, about 20 cm (8 in.) of line can be seen pulled through the fairlead as tension increased.

WAVE-INDUCED VESSEL MOTIONS

At a mooring exposed to waves, the wave-induced vessel motions, especially sway and roll, cause the vessel fairleads to move away from the pier. Such motions increase the distance between the ship's fairlead and the bollard on the pier, and as a result increase mooring line tension. Flory (1)

Figure 5 shows how this effect. The length of line when stretched by static wind and current forces is designated by Line Length 1. The wave-induced motions cause the vessel fairlead to move

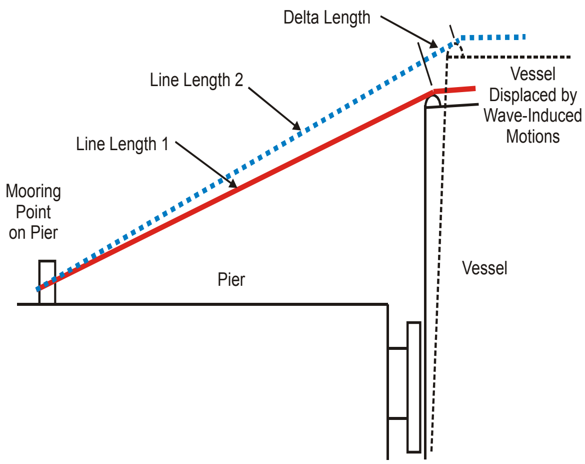

Figure 5 Mooring Line Stretch Due To Vessel Motion

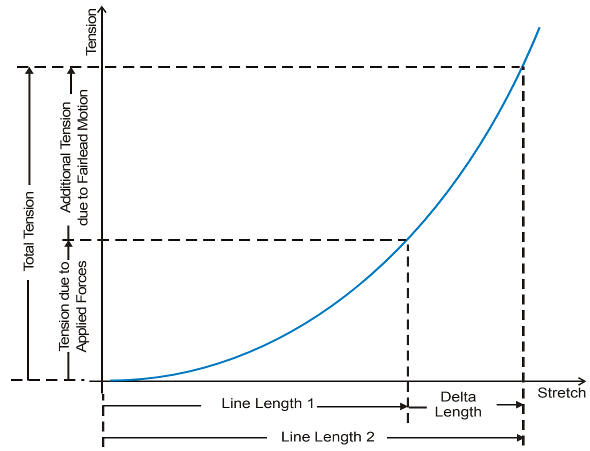

Figure 6 Increased Tension Due To Mooring Line Stretch on Tension

away from the bollard and stretch the line to Line Length 2. Delta Length designates the resulting increased mooring line stretch.

Figure 6 is a plot of rope tension vs. stretch. It shows how this wave-induced stretch increases mooring line tension. A typical nylon rope non-linear stretch characteristic is illustrated. Wind and current loads acting on the vessel tensioned the line and stretched it to Line Length 1. Wave-induced vessel motions stretch the line further to Line Length 2, and this increases tension in the line. When the mooring line stretch characteristic is non-linear, this tension increase is not proportional to stretch and can be significant.

Longer Tails Recommended

Synthetic fiber tails are sometimes shackled to the ends of wire ropes to increase mooring line stretch and thus reduce peak mooring tensions. Earlier editions of the Oil Companies International Marine Forum (OCIMF) *Mooring Equipment Guidelines* recommended the use of 11 m (36 ft) long nylon tails on some tanker wire-rope mooring lines to increase stretch. OCIMF (2) This recommendation was interpreted by many as a requirement to only use 11 m long tails.

As tanker size increased and as the tankers were moored in exposed locations, problems began to occur. The nylon tails were failing, due to high tensions and cyclic loading.

An earlier study for OCIMF had demonstrated that polyester rope was much more durable than nylon rope when subjected to tension cyclic loading in wet condition. Flory(3) Polyester rope is stiffer than nylon, but a polyester tail that is two to three times longer than the nylon tail it replaces will have about the same stiffness and would last much longer.

A recent study led by Tension Technology International (TTI) investigated this and other mooring line problems. TTI (4) As a result of that study, the recently published third edition of the OCIMF *Mooring Equipment Guidelines* clarified the recommendation, making clear that longer tails could and should be used when possible. OCIMF (5)

Better Nylon Ropes for Tails

Nylon rope is generally preferred for use as mooring line tails and other uses, such as towing lines and SPM hawsers, because of its greater elasticity.

The earlier OCIMF studies demonstrated that some grades of nylon yarn were much more durable than others when ropes are subjected to tension cyclic loading in wet condition. Flory (3) A yarn-on-yarn abrasion test was developed in that study to quantify this durability property. Flory (6) That yarn test is now a standard test method. Cordage Institute (7)

The Cordage Institute will soon publish a guideline to qualify "marine grade" nylon yarn through the use of that test method. Cordage Institute (8) Flory (9) The use of these "marine grade" nylon yarns greatly improves the cyclic load endurance of the rope.

Interstrand abrasion is the principal form of rope strength degradation during tension cyclic loading. The rope construction influences this interstrand abrasion. It is severe in braided rope and is less severe in twisted-strand (laid) rope.

The rope interstrand abrasion problem can be eliminated by protecting the nylon strands with braided polyester jackets. Such ropes are now used as shipboard mooring lines and as tails for offshore lightering. Huntley (10)

Special nylon ropes have now been developed for use in mooring wave-energy generators. Ridge (11) These ropes consist of many parallel "marine grade" nylon 3-strand sub-ropes encased in a braided outer jacket.

High-Performance Fiber Mooring Lines

Wire ropes have traditionally been used as mooring lines on large vessels, because conventional fiber ropes are too elastic and not strong enough.[4] High-performance fiber ropes are now replacing wire mooring lines for a number of reasons.

High-performance fiber ropes typically have about the same strength as a wire of the same size. These ropes typically stretch about twice as much as wire rope, but because of the catenary effect in wire rope mooring lines, these ropes have stiffness properties similar to those of wire rope when used as mooring lines.

High-performance fiber mooring lines are much lighter and are more flexible than the wire ropes which they replace. The fiber rope lines can be handled by fewer people on deck and on the dock, resulting in crew cost savings.

Another advantage is crew safety. The use of fiber rope mooring lines eliminates risks of cuts from broken wire "fishhooks" and greatly reduce risks of back injuries. Fiber ropes don't rust and don't require lubrication. Graf (12), Davis (13), Gilmore (14)

Gas carrier operators are now using HMPE mooring lines.[5] But these lines have experienced a higher than normal failure rate. MarineLink (15) TTI conducted a study of this problem in 2011. The study made an interim recommendation that longer tails be used to increase mooring line stretch and

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4 Conventional fiber ropes refers to ropes made of nylon, polyester and polypropylene fiber.

5 HMPE is high-modulus polyethylene

reduce peak tensions. It also recommended that the industry establish guidelines for specifying and testing HMPE rope mooring lines. OCIMF and the Society of International Gas Tanker and Terminal Operators (SITTGO) are now developing such guidelines.

If properly cared for, high-performance fiber rope mooring lines outlast wire ropes. But they are vulnerable to external cuts and abrasion. They are particularly vulnerable to damage as they run through fairleads.

A low-friction, low-abrasion nylon liner was recently developed to overcome this problem. Black (16) An example is shown in Fig. 7. The liner comes in two parts which can easily bolted together and retrofitted into existing fairlead onboard vessels.

Figure 7 Low-Friction, Low-Abrasion Fairlead Liner

PASSING SHIP PROBLEMS

The risks of passing ship problems increases as larger ships enter into and moor along confined channels. The larger vessels must pass closer to moored vessels to remain within the channel, and they must pass at higher speed to maintain steerage.

Studies of passing ship effects show that the forces and moments on a moored vessel increase as the passing vessel size increases and as the gap between the vessels decreases. These forces and moments also increase in proportion to the square of the passing vessel's speed. Flory (17), Seelig (18) Those past studies were based on model tests or computer analyses conducted for infinite waterways, without channel wall effects.

Passing ship effects in restricted channels have now been studied using computer simulation. Fenical (19), Flory (20) The study found that surge forces on a vessel moored alongside a vertical quay wall in a wide channel are essentially doubled, while the sway forces and yaw moments are essentially halved.

In a narrow channel, the surge forces are about double those in the single-quay-wall case, in effect quadrupling the passing-vessel-induced surge force expected in open water. The sway forces and moments also increase as compared with the single-quay-wall case. As at result, the motion response of the moored vessel is substantially altered and the peak mooring line loads can be substantially greater.

THE NEED FOR COMPUTER ANALYSIS

The effects of waves and passing ships on vessels moored alongside a pier can only be adequately determined through dynamic computer analysis, or through much more expensive model tests.

The OCIMF and SITTGO mooring guidelines now recommend computer analysis of tanker and gas carrier terminals. OCIMF (5) Many gas carrier terminals now require that a vessel's mooring system be vetted by computer analysis. The California State Lands Commission requires vetting of a vessel's mooring system in cases which might involve passing ship effects. California Building Code (21)

Two computer programs, Optimoor and Termsim, are now available which can perform dynamic analysis of vessel moorings in wave conditions. Banfield (22), van der Molen (23) The Optimoor program can calculate the passing-ship induced force and moment time histories for use in dynamic analysis. It can thus account for the additional mooring line load imposed by ship motions, discussed above.

CONCLUSIONS

Problems may be encountered as larger vessels are being moored at exposed piers in offshore locations and are entering harbors with confined channels.

Wave-induced vessel motions at exposed piers increase mooring loads and can fatigue and break mooring lines. Dynamic analysis computer programs should be used to evaluate potential problems such situations. Solutions include the use of longer or better tails on mooring lines and of high-performance fiber rope mooring lines. Retrofitting of fairleads may be necessary to prevent damage to the fiber rope mooring lines.

In confined channels, the larger vessels must pass closer to moored vessels in order to remain in the channel, and they may need to pass at greater speed in order to maintain steerage. Again, this requires dynamic computer mooring analysis. Vessel mooring arrangements may need to be enhanced, and channels may need to be widened.

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REFERENCES:

1. Banfield, S.J. and Flory, J.F., "Improved Mooring Line Technology for Tankers and Gas Carriers at Exposed Berths", OCEANS MTS/IEEE '09 Seattle, IEEE, Piscataway, NJ and MTS, Columbia, MD, 2009
2. OCIMF, *Mooring Equipment Guidelines*, 2nd ed., Oil Companies International Marine Forum, London, Witherby & Co., London, 1997
3. Flory, J.F., *Hawser Test Report, Data on Large Synthetic Ropes in the Used Condition*, OCIMF, Oil Companies International Marine Forum, Witherby & Co., London, 1982
4. Joint Industry Project, "Develop Effective Moorings for Tanker and Gas Carrier Terminals Exposed to Waves", CRT-1, Tension Technology International, Eastbourne, UK, 2006
5. OCIMF, *Mooring Equipment Guidelines*, 3rd ed., Oil Companies International Marine Forum, London, Witherby Seamanship International., Livingston, UK, 2008

6. Flory, J. F., Hearle, J.W.S. and Goksoy, M., "Abrasion Resistance of Polymeric Fibres In Marine Conditions", *2nd International Conference On Polymers In a Marine Environment*, IME, London, Oct. 1987
7. Cordage Institute, "Test Method for Yarn-on-Yarn Abrasion", CI 1503, Cordage Institute, Wayne, PA, 2009
8. Cordage Institute, "Performance Requirements for Marine Grade Nylon Yarn for Fiber Rope", CI 2009N, Cordage Institute, Wayne, PA, 2013
9. Flory, J.F., "Cordage Institute Guidelines for Marine Grade Nylon Rope-Making Yarns", OCEANS MTS/IEEE '13 San Diego, IEEE, Piscataway, NJ, MTS, Washington DC, 2013, publication pending.
10. Huntley, M.B. and Whitehill, A.S., "Retirement Criteria for Nylon Ropes", *OCEANS MTS/IEEE 2002 Biloxi Conference*, IEEE, Piscataway, NJ and MTS, Columbia, MD, 2002
11. Ridge. I.M.L, Banfield, S.J. and Mackay, J.,"Nylon Fibre Rope Moorings for Wave Energy Converters", *OCEANS MTS/IEEE 2010 Seattle Conference*, IEEE, Piscataway, NJ and MTS, Columbia, MD, 2010
12. Graf, G.H. and Whitehill, A.S., "A Field Study of Wire Lay Spectra Mooring Ropes", *Oceans '98 Baltimore*, IEEE, Piscataway, NJ and MTS, Columbia, MD, 2010, 1998
13. Davis, G.A., Huntley, M.B. and Correale, S.T., "Long Term Performance of Mooring Lines Made with Spectra Fiber", *OCEANS '06 Conference Proceedings*, IEEE, Piscataway, NJ and MTS, Columbia, MD, 2006
14. Gilmore, J., Miller, J. and Chou, R., "Mooring With High Modulus PolyEthylene (HMPE) Fiber Lines", *OSEA 2006 Conference*, Singapore, 2006
15. MarineLink, www.marinelink.com/news/mooring-dyneema-lines348178.aspx
16. Black, K., Flory, J.F., Banfield, S.J. and Ridge, I.M.L., "Low-Friction, Low-Abrasion Fairlead Liners", *OCEANS '12 MTS/IEEE Conference Hampton Roads*, IEEE, Piscataway, NJ and MTS, Washington, DC, 2012
17. Flory, J.F., "A Method for Estimating Passing Ship Forces", *Ports 2001 Conference*, ASCE, Reston, VA, 2001
18. Selig, W.N., "Passing Ship Effects on Moored Ships", Technical Report TN-6027-OCN, Navy Facilities Engineering Service Center, Port Hueneme, CA, 2001
19. Fenical, S., Kolomiets, P., Kivva, S. and Sheleznayak, M., "Numerical Modeling of Passing Vessel Impacts on Berthed Vessels and Shoreline", *International Conference on Coastal Engineering*, ASCE, Reston, VA, 2006
20. Flory, J.F. and Fenical, S., "Quay Wall Influence on Passing-Ship Induced Mooring Loads", *ASCE Ports 2010 Conference*, ASCE, Reston, VA, 2010
21. "Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS)", *California Building Code, Chapter 31F, Marine Terminals,* California State Lands Commission, Long Beach, 2010
22. Banfield, S. and Flory, J., "Effects of Fiber Rope Complex Stiffness Behavior on Mooring Line Tensions With Large Vessels Moored in Waves", OCEANS '10 Seattle, IEEE, Piscataway, NJ, MTS, Columbia MD, 2010
23. van der Molen, W., Ligteringen, H., van der Lem, J. and de Waal, J., "Behavior of a Moored LNG Ship in Swell Waves", J. Waterway, Port, Coastal, Ocean Eng., 129(1), 15–21, 2003